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III. Simulation of Disease Spread and Impact

W.J. Bloomberg
Pacific Forest Research Centre
Report BC-R-7

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III. SIMULATION OF DISEASE SPREAD AND IMPACT

By

W.J. Bloomberg

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Environment Canada
Canadian Forestry Service
Pacific Forest Research Centre
506 West Burnside Road
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SUMMARY

A computer simulation program RREST written in FORTRAN IV PLUS is described which uses estimates of *Phellinus weirii* (Murr.) Gilbertson spread rate and impact on tree growth to predict infested area increase and volume increment reduction in Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands after a specified number of years. The model also produces simulated transect surveys of infected stands using four sampling methods for comparison with ground surveys for *P. weirii* incidence. Results are printed as tables, maps, and graphs.

Necessary input values for disease spread rate and impact on volume increment can be supplied either from default values, i.e., values already built into the model, or from those specified by the user. Default spread rate values were obtained from five permanent plots over periods from 32 to 52 years. Values for increment reduction were derived from published and unpublished data. Stand input data can be supplied either from the results of a ground survey analysis or by the user. Other inputs for which default values or user specifications are required include number of centers, length of growth cycle, and random number series for random distribution of centers. Inputs which must be supplied by the user include current and projected ages of stands, stand ages for simulation survey and survey method, and stand ages for map and tabular results. Examples of data inputs are given.

Model accuracy was tested by comparison of predicted with actual infested areas in 10 infection centers in a plantation at ages 15, 25, and 35; predicted areas were 58, 102, and 107% respectively of the ground areas measured from stem maps.

Predicted volume increment reduction in infection centers was 14.4% compared with average measured volume increment reductions of 14.1% in four 30- to 40-year-old natural stands. In eight stands, approximately age 40, with ground survey estimates of infection ranging from 3.6 to 18.8%, simulated transect survey estimates averaged 108% of ground survey estimates and 98.4% of the actual simulated infested area. The predicted percent of area infested at age 80 ranged from 15.3 to 47.6% for visible area infested and from 24.5 to 76.2% for total area infested. Predicted volume increment reduction ranged from 54.1 to 67.4% in centers and from 13.2 to 49.9% on a stand basis.

RESUME

L'auteur décrit un programme de simulation par ordinateur RREST rédigé en FORTRAN IV PLUS employant des estimations du taux de propagation de *Phellinus weirii* (Murr.) Gilbertson et de son effet sur la croissance des arbres pour prévoir l'augmentation de la superficie infestée et la réduction de l'accroissement en volume dans des peuplements de Sapins Douglas (*Pseudotsuga menziesii* (Mirb.) Franco) après un certain nombre d'années. Le modèle simule également des relevés par transects des peuplements infestés avec quatre méthodes d'échantillonnage pour la comparaison avec des relevés sur le terrain de l'incidence de *P. weirii*. Les résultats sont imprimés sous forme de tableaux, de cartes et de graphiques.

Les données nécessaires pour le taux de propagation de la maladie et l'effet sur l'accroissement en volume peuvent être soit des valeurs implicites, c'est-à-dire des valeurs déjà introduites dans le modèle, soit des valeurs précisées par l'utilisateur. Les valeurs implicites pour la propagation proviennent de cinq parcelles permanentes et couvrent des périodes de 32 à 52 ans. Celles pour la réduction de l'accroissement sont tirées de données publiées et non publiées. Les données concernant les peuplements peuvent être les résultats d'un relevé sur le terrain ou être fournies par l'utilisateur. D'autres valeurs implicites ou fournies par l'utilisateur sont également nécessaires: le nombre de foyers, la longueur du cycle de croissance et une série de nombres aléatoires pour la distribution aléatoire des foyers. L'utilisateur doit, de plus, indiquer les âges actuels et projetés des peuplements, les âges des peuplements pour le relevé par simulation et la méthode de relevé, et les âges des peuplements pour les résultats sous forme de cartes et de tableaux. Des exemples de données sont fournis.

L'exactitude du modèle a été contrôlée par comparaison des superficies touchées réelles et prévues dans 10 foyers d'une plantation à 15, 25, et 35 ans d'âge, et la correspondance entre les superficies prévues et les superficies déterminées à partir de plans-projections est de 58, 102, et 107% respectivement. Pour la réduction de l'accroissement en volume dans trois peuplements naturels de 40 ans, le pourcentage prévu était de 24,2% alors que le pourcentage moyen mesuré est de 21,2%. Pour huit peuplements d'un âge approximatif de 40 ans, où les niveaux d'infection estimés par des relevés au sol variaient entre 3,6 et 18,8%, la correspondance des estimations tirées des relevés simulés par transects est en moyenne de 108% avec les estimations fournies par les relevés sur le terrain et de 98,4% avec l'étendue atteinte réelle déterminée par simulation. Le pourcentage prévu pour la superficie atteinte à 80 ans varie entre 15,3 et 47,6% pour la superficie visible et entre 24,5 et 76,2% pour la superficie totale. La réduction prévue de l'accroissement en volume varie entre 54,1 et 67,4% dans les foyers et entre 13,2 et 49,9% au niveau du peuplement.

INTRODUCTION

Owing to the dynamic behavior of *Phellinus weirii* (Murr.) Gilbertson root rot in second-growth Douglas-fir (*Pseudotsuga menziesii* (Mirb.) Franco) stands, forest managers are forced to take spread of infection into consideration when drawing up working plans. The disease, which is estimated to destroy more than one million cubic metres of timber in British Columbia every year, originates from infected stumps of previous stands and spreads at points of contact between healthy and diseased roots (Wallis 1976a). Effects of the disease are growth reduction followed by mortality (Nelson 1980; Wallis 1976a). Managers can obtain estimates of current stand losses due to the disease from surveys for incidence of infection, i.e., percent area infested and numbers and sizes of infection centers (Bloomberg et al. 1980a, b), and from average tree-growth losses in infection centers (Bloomberg and Wallis 1979; Ford 1977; Gillette 1975; Thies 1983). In the absence of long-term field data, future stand-growth losses and mortality must be estimated using average rates of disease spread and tree-growth reduction and killing as functions of the number of years since infection (Ford 1977). The necessary calculations are complex, involving computation of the spread of individual infection centers of different sizes and the growth loss in stand areas which became infested at different times. A computer model is the most efficient means of making the necessary calculations.

Described here is a computer model called RREST (Root Rot Estimator) which performs these calculations[1]. An additional function performed by the model is to simulate transect surveys similar to ground surveys on which the estimates of infection are based, thereby allowing comparison of the ground survey results with those of simulated surveys.

THE MODEL

The model is written in FORTRAN IV PLUS and requires approximately 48K (decimal) bytes of storage. It utilizes stand data from two alternate sources—results of root disease surveys or data supplied by the user of the model. Survey results are obtained by the computer from a file which is prepared by the survey analysis program (Bloomberg et al. 1980b). The user can choose the input mode as batch (data from punch cards or a computer file) or online (data entered as responses to requests displayed on a computer terminal).

Scale

In order to minimize execution time (approximately three minutes on a Digital/PDP 11/45 computer), the model bases calculations on randomly drawn subsamples of a stand. Each subsample contains a specified number of infection centers within a 100 x 100 matrix (up to a maximum of 25 in the current version of the model). Area of the subsample is calculated from stand area and total number of infection centers to reproduce the same density of centers as in the whole stand, i.e.:

$$\text{area of subsample} = \text{stand area} \times \left(\frac{\text{specified no. of centers in subsample}}{\text{total no. of centers in stand}}\right)$$

The fixed number of centers per subsample ensures a sufficient number for comparisons among stands with widely varying numbers of centers. Scale of the 100 x 100 matrix (plot) is calculated from the subsample area, i.e.:

$$\text{scale (m)} = \sqrt{\text{subsample area}}$$

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[1] Program listing available on request to the author.

Distribution, Size, and Shape of Infection Centers

For each run, different pseudorandom number series (IBM 1970) can be generated to create different random distributions of centers, thereby simulating several randomly drawn subsamples of a stand from which a mean and coefficient of variation can be calculated. In order to create specific distributions, infection centers can be positioned within the plot matrix by specifying their x and y coordinates. Areas of centers (square metres) at specified stand ages can be assigned individually or proportionally, i.e., by apportioning the total number of centers per subsample into specified size classes (up to a maximum of five size classes in the current version). The proportion of centers within each size class is provided by ground survey results or can be specified by the user. Shape of centers can be varied from a narrow ellipse to a circle by specifying different incrementation factors for the major and minor axes of each center. Orientation of individual centers within the plot matrix is achieved by varying the angles of major axes relative to the x axis either by user specification or by randomization within the model. The variable shape and orientation features were included in the model to allow for simulation of specific disease distributions and for evaluation of their effects on accuracy of transect surveys. Specification of individual center sizes, locations, and shapes is permissible only in batch mode and for stand data supplied by the user. For stand data supplied in online mode or from survey results, centers are distributed randomly.

Spread Rate of Infection

Disease spread rate in the model is specified as radial extension of the disease in centimetres per time period (centimetres per growth cycle in years). The current version of the model allows 20 periods, e.g., a growth cycle of 5 years would permit simulation of 100 years. In the model, centers expand by extending axes of ellipses by a basic spread rate modified by the major and minor axis incrementation factors in order to produce different shapes. Thus, some centers can be simulated to grow faster than others or in different directions. However, for stand data supplied in online mode or from survey results, centers are made to spread at the same rate along both axes, i.e., isodiametrically. Sizes of centers are calculated from the area falling within the ellipse after each incrementation of their axes and are recorded as points in the plot matrix (Fig. 1). The model calculates the area infested by root rot as "visible area", i.e., with aboveground symptoms (Wallis 1976a) and as a total area, i.e., visible area plus additional area with trees having only below-ground symptoms (Wallis and Bloomberg 1981). Rounding-off decimal distances to coordinate points in the plots may cause small (less than 1%) discrepancies in area. No expansion of infection-center perimeters is permitted where they adjoin those of other centers, i.e., where two or more centers merge nor where they abut on the plot-matrix boundary. Depending on particular random distribution of centers, the latter constraint may result in some over- or underestimation of total center area (less than 10%) in a particular subsample but is averaged out over several samples.

The model may be used to simulate root rot spread in newly formed stands in which infection centers have not yet developed or in older stands already containing infection centers. In new stands, center locations are assigned but no spread occurs until spread-rate values exceed zero. In older stands, time of initiation for each center is determined through successive reductions of axis lengths by the specified spread rate for each previous growth cycle. The growth cycle containing the smallest positive values for both axes is designated as the stand age at initiation of the centers. Centers which exceed 1 grid unit in area at growth cycle 1 are automatically set to 1 unit and their spread rates proportionately increased to allow them to attain the required size by the stand age. This procedure allows for centers which have enlarged by merging with other centers; subsequent spread rates for such centers are reduced to the specified rate.

Growth Impact

In the model, percent reduction of volume increment in each infection center is calculated by multiplying the area newly infested in each growth cycle (disease extension area) by the specified percent reduction for that growth cycle, then summing the products for all disease-extension areas within a center and dividing by total center area to obtain the weighted mean increment reduction for the whole center:

$$IR_c = (A_1R_{I-1} + A_2R_{I-2} + \ldots A_IR_1)/A_c$$

where IR_c is the mean reduction in center c

A_1, A_2, ... A_I are disease-extension areas newly infested in growth cycles 1, 2, ... I and R_{I-1}, R_{I-2}, ... R_1 are the percent-increment reductions for the number of growth cycles elapsed since extension-area initiation up to the current growth cycle R_I. A_c is the total area of center c. Mean increment-reduction percent

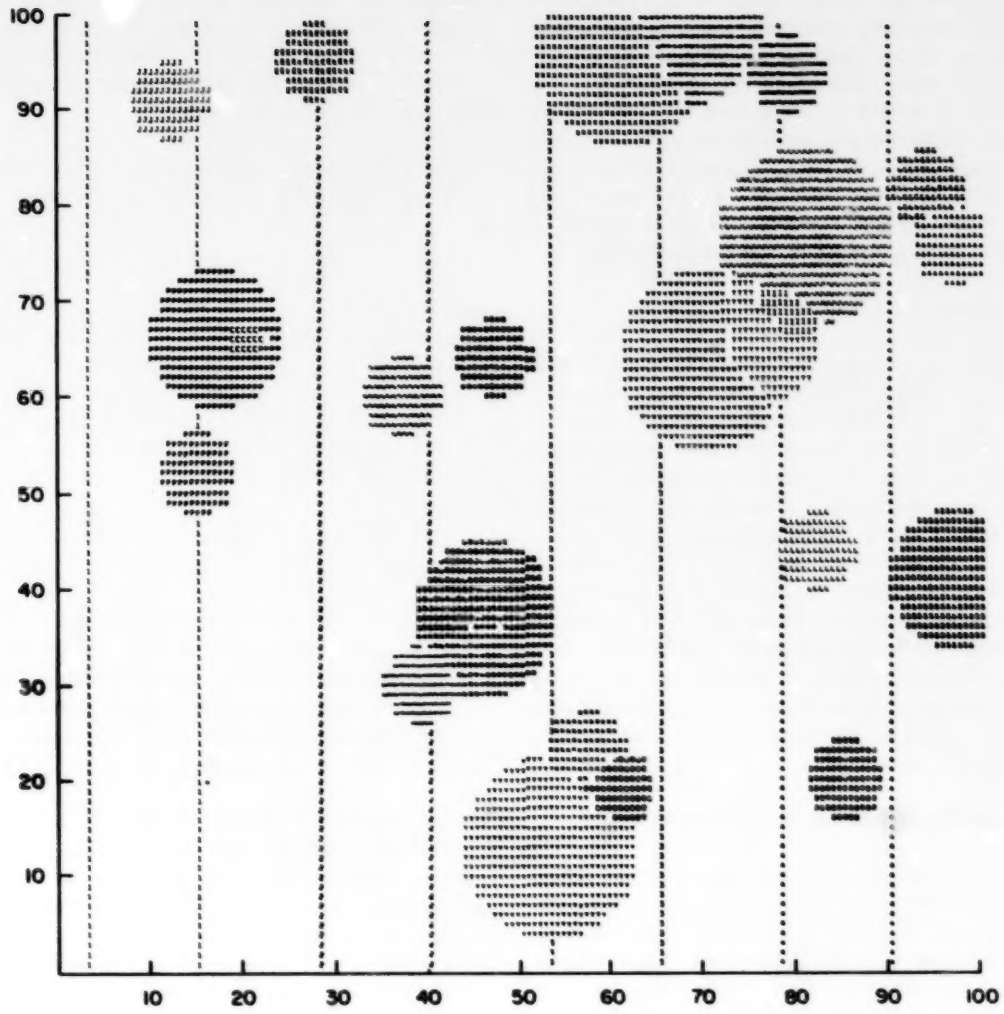

Fig. 1. Map of infection centers and survey transects produced by computer simulation model RREST. Centers are identified by symbols and transects by number. Note merging of centers.

for the entire stand is calculated by summing the products in cohorts of disease-extension areas infested in the same growth cycles in all centers and dividing by stand area. The percent-increment reduction in each growth cycle is defined as a function of the period elapsed since each extension area became infested and the stand age at infection. Basic increment-reduction percentages are specified for each number of growth cycles elapsed and the basic reduction is modified by a severity factor depending on stand age at time of infestation. Mortality is defined as 100% increment reduction, i.e., trees are stopped from growing, and mortality area is the sum of extension areas having 100% increment reduction.

Simulation of Transect Survey

Sampling by transects through a subsample of a stand is simulated by selecting transect-starting points along the x or y axes of the plot matrix (Fig. 1). Selection can be by randomization, with or without replacement; by systematic intervals following a random start; or by specification of all start points. Transects are defined as lines passing perpendicularly from one side of the plot to the opposite site. Total length of segments of transects falling within simulated infection centers forms the basis of an estimate of infested area using the intersection-length method (Bloomberg et al. 1980a). Transects are grouped to form "grids." Two or more grids can be used to obtain independent sample estimates of mean infection area and coefficient of variation.

Default-Spread Rates and Growth-Impact Values

The model permits the user to enter the basic spread rates for each growth cycle, the basic impact rates for number of growth cycles elapsed since infection, and the severity factors for each stand age. Alternatively, the user can accept default values for these variables, i.e., values already built into the model.

The default value for spread rates in all growth cycles was set at 35 cm/yr. This spread rate was based on published data and measurements of 14 centers in five permanent plots established from 1928 to 1950 in 15- to 50-year-old Douglas-fir stands at Cowichan, B.C. (Wallis 1976b). Plots were examined at 2- to 10-year intervals. In five centers, all trees with aboveground *P. weirii* symptoms were recorded and mapped at each examination. In the remaining nine centers, only killed trees were mapped and dates of death recorded. For centers with all infected trees mapped, boundary limits, as defined in Bloomberg et al. (1980b), were joined and the enclosed areas measured with a planimeter. Mean radius of each of these centers was calculated from its area at each examination date. In all centers, rate of spread was also calculated from the mean distance from the presumed origin of infection to the most distal trees killed by *P. weirii* at each examination date. Ratio of mean distal tree distance to mean radius was calculated for centers measured by both methods.

Rate of spread was generally very uniform over the 40-year observation period (Fig. 2). Overall rate of

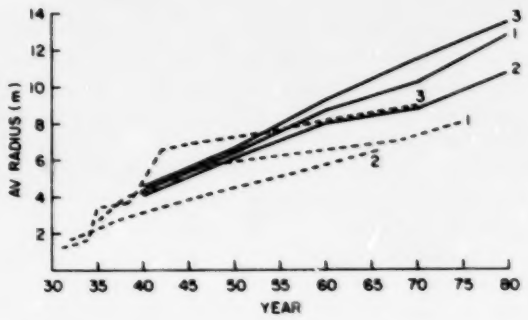

Fig. 2. Average radial spread of three *Phellinus weirii* infection centers in second-growth Douglas-fir stands. Broken and solid lines represent spread calculated by distance to distal-infected trees and by area measurement on stem maps respectively.

radial extension measured by mean distance to most distal-killed trees averaged 24.4 (17-43) cm/yr. In centers measured by both methods, distal-killed tree distance averaged 0.77 (0.73-0.86) of mean center radius due to omission from the former method of live infected trees distal to the outermost-killed trees in centers. Average rate of boundary extension for all centers was therefore calculated as 24.4/0.77 = 32 cm/yr. This rate is close to those of McCauley and Cook (1980) (34 cm/yr) and Nelson and Hartman (1975) (35 cm/yr) in different conifer types in the Pacific Northwest.

Provisional default values for basic percent-volume-increment reduction were as follows, based on published and unpublished data for impacts and allowing for 5-15 years delay in appearance of symptoms following infection (Wallis 1976a): 5, 10, 20, 50, 80, and 100% volume-increment reductions at 0-5, 6-10, 11-15, 16-20, 21-25, and 26+ years respectively after initiation of infection. Several reports have been

Table 1. Percent increment reduction in second-growth Douglas-fir infected by *Phellinus weirii* reported from various sources

Years From Start of Reduction	Thies (1983)[a] Volume			Gillette (1975)[b] Height				Bloomberg and Wallis (1979)[c] Height				Wallis (unpubl.) Height			Default Values[d]
	Living	Dead	Avg	Plot A	Plot C	Plot E	Avg	Stand 1	Stand 2	Stand 3	Avg	Plot 1	Plot 2	Avg	Avg
1-5	2.6	0	1.3	12.6	12.8	7.1	10.8	9.3	6.7	5.4	7.1	13.4	21.0	17.2	10
6-10	5.3	33.7	19.5	20.0	12.9	32.0	21.6	31.0	54.1	18.7	34.6	23.2	32.8	28.0	20
11-15	17.9	45.4	31.6	41.7	16.7	35.0	31.1			43.6	43.6		69.5	69.5	50
16-20													87.0	87.0	80
21+															100

[a] Measured from author's Figure 1.

[b] Measured from author's Figures 2, 3, and 4.

[c] Using original data from which average results were reported.

[d] See text for definition of default values.

made on the effect of *P. weirii* on tree height and diameter growth (Bloomberg and Wallis 1979; Ford 1977; Gillette 1975), but only one report is currently available on the effect of the disease on tree volume with increasing time (Thies 1983). All studies were made in Douglas-fir stands 40-60 years old and showed sharply decreasing tree-growth rates (Table 1). Percent reduction for height and volume increment were of similar magnitudes, taking into account that Thies's data included infected trees with no above-ground symptoms and that the others were based on trees with moderate to severe symptoms. Wallis's (unpublished) data were based only on trees with severe symptoms.

Default values for severity factors (SF) modifying the basic increment reductions (BIR), according to stand age, were derived from the observed periods elapsed from first appearance of symptoms until death of tree (Table 2). Thus, the severity factor at age "a" must be such that $BIR_i \times SF_a$ is greater than or equal to 100, where i is the number of growth cycles that must elapse from initial infection to death of tree. For example, sapling Douglas-fir infected with *P. weirii* before age 5 invariably die within 5 years (Wallis unpublished data), i.e., BIR = 5.0, SF = 20.0; whereas with increasing size, trees may take up to 15 years after infection to show symptoms (Wallis 1976a) and a further period of up to 10 years before death occurs. Trees infected at age 50+ years are assumed to survive until rotation age 100.

TESTING THE MODEL

Spread Rate

To date, only limited testing of the accuracy of the model has been possible due to insufficient long-term field data. Field data for testing the accuracy of infection-spread predictions were obtained from a 2.9 ha Douglas-fir stand planted near Campbell River, B.C., in 1943 and examined at 3- to 5-year intervals

Table 2. Estimated severity factors for volume increment reduction in Douglas-fir based on stand age and period elapsed since infection by *Phellinus weirii* to death of tree

Stage Age at Infection	Years to Death	Severity Factor
0-5	1-5	20.00
6-11	6-10	10.00
11-15	11-15	5.00
16-20	16-20	2.50
21-25	21-25	2.00
26-30	21-25	1.75
31-35	26-30	1.50
36-40	26-30	1.25
41-45	26-30	1.00
46-50	40-45	0.90
51-55	46-50	0.90
56-60	51+	0.80
61-65		0.80
66-70		0.70
71-75		0.60
76-80		0.60
81+		0.50

from age 15 (Wallis 1976b). Model predictions of average infested area with aboveground symptoms (visible area) in 10 infection centers at stand ages 15, 25, and 35 were 58, 102, and 107% respectively of the areas measured from stem maps. Although the percentage of infested area predicted by the model using the default rate of 35 cm/yr was about half that measured in the plantation at 15 years of age, it was almost exactly that measured at 25 and 35 years of age. The large difference in the earliest age was partly due to the difficulty of accurately measuring infection centers at initiation, since the infested area was defined by only one or two trees and was probably overestimated.

Growth Reduction

Data for testing the accuracy of the model in predicting increment reduction was obtained from measurements of 17 infection centers in four naturally established Douglas-fir stands approximately 30-40 years old near Cowichan, B.C. (Bloomberg unpub-

Table 3. Disease spread and volume increment reduction in second-growth Douglas-fir stands infected with *Phellinus weirii*, as predicted by model RREST

		% Area Infested[a]			% Increment Reduction	
Stand No.	Age	Mortality	Visible[b]	Total[c]	Centers	Stand
1	40	0.6	3.6	5.7	22.7	1.3
	80	10.3	15.3	24.5	54.1	13.2
2	40	0.3	4.5	7.2	16.3	1.2
	80	14.9	22.5	36.0	52.7	18.9
3	40	0.4	5.7	9.1	18.2	1.6
	80	19.8	28.2	45.1	56.1	25.3
4	40	1.4	9.0	14.4	24.6	3.5
	80	23.6	27.3	43.2	63.1	27.3
5	40	1.8	12.3	19.7	22.7	4.5
	80	34.1	40.2	64.3	62.5	40.2
6	40	1.2	12.4	19.3	17.8	3.4
	80	39.3	47.6	76.2	63.6	48.5
7	40	2.9	13.8	22.0	27.8	6.1
	80	32.8	35.5	56.7	67.4	38.2
8	40	3.4	18.8	30.0	25.5	7.7
	80	43.4	46.4	74.2	67.3	49.9

[a] Percent area infested at age 40 was obtained from ground surveys.

[b] Visible infection area includes mortality area.

[c] See text for definition of total infection area.

lished data). In 10 m-wide transects running from 10 m within the healthy stand through the presumed origin of infection to 10 m within the healthy stand on the opposite side of the infection center, sample trees were felled and dissected by stem analysis to determine their periodic increment. Increment was averaged along the transect and reduction expressed as percentage of increment in the healthy stand. Model estimates of volume-increment reduction in infection centers was 14.4% compared to actual average reduction of 14.1% for the four stands.

For eight stands approximately 40 years old with ground-survey estimates of infection ranging from 3.6 to 18.8% of stand areas, infested-area percent predicted by the model at age 80 ranged from 15.3 to 47.6% for visible area and from 24.5 to 76.2% for total infection (Table 3). Predicted volume-increment reduction at age 80 in centers ranged from 54.1 to 67.4% and in stands from 13.2 to 49.9%. In stands with up to about 12% of areas visibly infested at age 40, area infested at age 80 was a significant ($p = 0.05$) linear function of area infested at age 40 (Fig. 3). In stands with a higher percentage infesta-

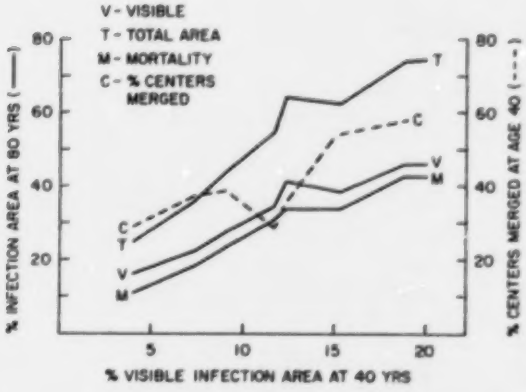

Fig. 3. Relationships of visible mortality and total infection area at stand age 80 and percentage centers merged at age 40 to visible infection at age 40 predicted by computer simulation model RREST in Douglas-fir stands infected with *Phellinus weirii*.

tion at age 40, the linear trend flattened out due to merging of centers. Field-survey data for a 70- to 80-year-old stand (Bloomberg unpublished data) show that as much as 50% of stand area may be visibly infected by *P. weirii*. In a 60-year-old stand, 52% of the trees were infected by the disease (Tkacz and Hansen 1982).

Comparison With Transect Surveys

Data for comparing field-survey results with results of simulated transect surveys were obtained from eight surveys carried out in the Duncan, Campbell River, and Squamish forest districts of the Vancouver Forest Region. Effects of infection-center spread pattern, survey design, and intensity on survey accuracy were investigated in eight centers from the Campbell River plantation. Simulated survey estimates averaged 108% (86.0-111.0%) of the ground-survey estimates and 98.4% (77.4-102.3%) of the true simulated infested area. In a simulated stand, percent difference of survey estimates from true infection area ranged from -34.3 to +2.3% using different combinations of spread pattern, survey design, and intensity (Table 4). Except in random transect allocation, four transects per grid gave more accurate results than two or three. Oblong centers resulted in less accurate results than circular ones at the lowest sampling intensity (2 x 2). Transects located at systematic intervals gave most accurate results; grids with random starting points and systematically located transects were almost as accurate and randomly located grids and transects were least accurate.

OPERATION OF MODEL

The model is operated by entering the command RUN RREST and then supplying the necessary inputs either by keying from a computer terminal or by preparing a batch file. Input mode option is determined by answers to four questions displayed on the terminal immediately after the program starts (Appendices 1 and 2). In online mode, all inputs must be keyed in at a computer terminal. In batch mode, all inputs must be supplied from a computer file prepared by the user.

Stand Data Options

Stand data comprises stand size (hectares) and number and sizes of infection centers in a stand. The data is supplied using one of four options.

Online-Survey Results. This option requires that a root-disease survey has been analyzed by program RRSAMP (Bloomberg et al. 1980b), thereby creating the necessary input file containing stand data. The name of this file must be entered at the terminal in response to the appropriate question.

Table 4. Effect of infection-center spread pattern, survey design, and intensity on accuracy of estimated area in *Phellinus weirii* infection centers simulated by model RREST

Spread Pattern	% Area Infested (actual)	Survey Design[a]	Survey Intensity[b]	% Area Infested (estimated)	% Difference
Circular	16.6	RG	2 x 2	12.8	-22.9
		RG	2 x 3	11.7	-29.5
		RG	2 x 4	19.6	+18.1
Oblong	17.5	RG	2 x 2	11.5	-34.3
		RG	2 x 3	15.7	-10.3
		RG	2 x 4	17.9	+2.3
Circular	8.2	RG	2 x 4	9.0	+9.7
		RT	2 x 4	3.4	-58.6
		AT	1 x 8	8.2	0

[a] RG = Random grid start points with systematic transect locations within grids.
RT = Transect locations randomly assigned.
AT = Transect locations systematically assigned within 1 grid.

[b] First digit is number of grids; the second is number of transects per grid.

Online-User Data. This option requires that stand data be supplied by keying in appropriate answers to the questions displayed at the terminal.

Batch-Survey Results. The name of the survey file containing stand data must be contained in the batch-input file.

Batch-User Data. Stand data must be included in the batch file.

Default Option

All default values for disease spread rate, increment reduction, and random-number series are used and no requests are made to enter these values. If no defaults are specified, values must be supplied either in the batch file or by keying from the terminal. In online mode, the default values are displayed at the terminal and changes are requested.

Confirmation Message Option

All entries keyed at the terminal are displayed and confirmation is requested before they are accepted by the model. Changes to entries may be made at this time. No confirmation messages are displayed if the option is declined.

Batch-File Preparation

A batch file consists of a series of records (punch cards) containing the necessary inputs for operation of the model (Appendix 3). The file is required only if the batch option is specified. Contents of the file differ according to the options requested as follows.

Survey Results-Defaults. Records 1, 12, 14, and 15 only are required. If a simulated survey is requested by record 12 using specified transect locations (method 4), record 13 is also required.

Survey Results-No Defaults. Records 1, 6, 9, 10, 12, 14, and 15 are required. If the projected stand age (record 1) exceeds 16 growth cycles, two consecutive records are necessary for each of records 6 and 10.

User Data-Defaults. Records 1, 11, 12, 14, and 15 are required. Record 11 must consist of two consecu-

tive records containing 16 initial center sizes in the first and 9 in the second.

User Data-No Defaults. Records 1, 2, 6, 9, 10, 11, 12, 14, and 15 are required, depending on the number of growth cycles and centers. If locations of centers are to be specified (record 2), records 3 and 4 are required, containing as many coordinates as there are centers. If angles of center axes are specified, record 5 is required. If axis-incrementation factors are to be specified, records 7 and 8 are required. The latter two records will each consist of two records, if the number of centers specified exceeds 16.

A data-input sheet (Appendix 4) can be used to simplify preparation of batch files.

MODEL OUTPUT

Output from model RREST (Appendix 5) consists of tables and maps for each of the stand ages for which they were requested (records 14 and 15). For each infection center, a table of individual infection centers shows their map symbols, coordinates, axis rotation angles, spread rates (centimetres per growth period), area (square metres), and percentage of stand area infested (Appendix 5-1). A summary table shows aggregate infection area for visible symptoms and for total infection in square metres and as percentage of the stand as a whole (Appendix 5-2). Mortality area (area with killed trees) is included in infection area but is also shown separately as percentage of infected area and stand area. Percent-volume increment loss is shown for the visibly infected area, the total infected, and the total stand area. Graphs show trends of infected area and increment loss over time from stage age 1 to the projected stage age. Trends are shown separately for visible infection, total infection, and stand areas (Appendix 5-3). Maps show locations and sizes of infection centers and the locations of simulated sample transects (Fig. 1). Calculations of simulated survey results are shown in a table giving the starts and ends of intersection lengths along each transect, calculated infected area by transect and by grid, and mean and coefficient of variation for the stand.

REQUIRED MODIFICATIONS TO SURVEY ANALYSIS PROGRAM[2]

Minor modifications are needed for the survey analysis program RRSAMP (Bloomberg et al. 1980b) in order to create the stand-data file for use with the survey option of the root disease simulation program RREST. These modifications include an additional survey-method option (no. 6) which calculates infection-center sizes from their intersection lengths. The calculation derives a diameter for each center based on the assumption that average intersection length falls at the midpoint between the maximum possible (the full diameter) and the minimum (outer edge) of the centers. Survey-method options 1-3 use measured or estimated center areas to create the stand-data file. Options 4 and 5 estimate total intersection length only and do not create a stand-data file; therefore, the survey results using the latter two options cannot be used as inputs to the simulation model. In these cases, the data should be reanalyzed using option 6.

The stand-data file includes the stand area, total number of infection centers, and the proportion of centers in the size classes used for the survey. The simulation program calculates individual center areas from the mean point of each size class. Therefore, it is important that size-class limits for each survey be set so as to stratify the infection-center population into as homogeneous groups as possible. For example, if the population consists of many small centers and a few very large centers, size-class limits should be set to include all the small centers in one class and the large centers in another. If, on the other hand, the size-class limits are set so that some of the centers in the upper size range of small groups are included with the large group, the mean point of the size class would not be representative of either group. Thus, center sizes calculated by RREST would not reflect those recorded in the survey. In the event that the uppermost size class set in the survey analysis is too small for the largest centers recorded, the survey analysis program sets an upper limit 50% greater than the largest center encountered. Optimum arrangements of size-class limits can easily be accomplished by inspection of the table of individual center sizes produced as one of the outputs from the survey analysis program.

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[2] Modifications are included in version 3.1 of program RRSAMP, updated December 1982. A copy of the program can be obtained on request to the author.

CONCLUSION

The root disease simulation model RREST uses the best available information on spread and impact on growth of second-growth Douglas-fir stands to provide forest managers with an estimate of how the disease will affect stands over their rotations. Where local knowledge is available for disease-spread and impact rates, this knowledge can be substituted for the default rates. As more detailed information becomes available on the disease dynamics of *Phellinus weirii*, it will be used to refine the model and increase its accuracy.

ACKNOWLEDGEMENTS

Provision of data on spread of infection and tree-growth reduction by G.W. Wallis is greatly appreciated.

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APPENDIX 1

Example of questions displayed and answers keyed in at a computer terminal for operation of root disease simulation model RREST. (Options = Online, User data, Defaults, No confirmation messages.) Keyed entries are underlined.

RUN RREST

This program projects future root rot losses based on batch or online inputs supplied by user or results from a root rot survey analysis. Please respond to requests entering data according to indicated input formats separated by commas. For further information, contact Dr. W.J. Bloomberg, Pacific Forest Research Centre, 506 West Burnside Road, Victoria, B.C. V8Z 1M5, phone (604) 388-3811. If program exits, check input and restart. Input begin:

ENTER OPTION FOR CONFIRMATION MESSAGES:
1 MESSAGES
2 NO MESSAGES
ENTER 1 or 2 2

ENTER OPTION FOR SPREAD AND IMPACT RATE VALUES:
1 DEFAULT VALUES
2 SUPPLIED BY USER
ENTER 1 or 2 1

ENTER DATA INPUT MODE:
1 FROM ONLINE INPUTS
2 FROM BATCH INPUTS
ENTER 1 or 2 1

ENTER STAND DATA SOURCE:
1 FROM SURVEY RESULTS
2 FROM USER INPUTS
ENTER 1 or 2 2

ENTER STAND AREA (HA), AV. NO. INFECTION CENTERS/HA
(2F5.1) 50.0,3.0

ENTER NO. OF INFECTION CENTER SIZE CLASSES (MAX. 5)
FOLLOWED BY UPPER SIZE LIMITS (HA) FOR EACH SIZE CLASS
IN ASCENDING ORDER (I5, 5F5.2) 3,0.05,0.01,0.10

ENTER PERCENTAGE OF CENTERS IN EACH OF THE 3 SIZE CLASSES
(5F5.0) 60,20,20

ENTER CURRENT STAND AGE, PROJECTED AGE AND GROWTH CYCLE (YRS) (3I3)
40,70,5

ENTER STAND AGES FOR MAP OUTPUTS (20I3)
(0 For No Maps) 40

ENTER STAND AGES FOR SUMMARY TABLE OUTPUT (2013)
(0 For No Tables) 40

ENTER STAND AGES FOR SAMPLING (2013)
(0 For No Samples) 40

ENTER NO. OF GRIDS AND TRANSECTS PER GRID (213) 2,2

ENTER SAMPLING METHOD AS FOLLOWS:
(1) RANDOM WITHOUT REPLACEMENT
(2) RANDOM WITH REPLACEMENT
(3) SYSTEMATIC TRANSECT LOCATIONS WITH RANDOMIZED GRID STARTS
(4) ASSIGNED TRANSECT LOCATIONS
ENTER 1, 2, 3, or 4 3

INPUTS NOW COMPLETE. AWAIT TERMINATION MESSAGE.

APPENDIX 2

Example of questions displayed and answers keyed in to a computer terminal for operation of root disease simulator mode RREST. (Options = Online, Survey data, No defaults, No confirmation messages.) Keyed entries underlined.

```
RUN RREST

This program projects future root rot losses based on batch or online inputs supplied by user or results from a
root rot survey analysis. Please respond to requests entering data according to indicated input formats separated
by commas. For further information, contact Dr. W.J. Bloomberg, Pacific Forest Research Centre, 506 West
Burnside Road, Victoria, B.C. V8Z 1M5, phone (604) 388-3811. If program exits, check inputs and restart. In-
puts begin.

ENTER OPTION FOR CONFIRMATION MESSAGES:
1 MESSAGES
2 NO MESSAGES
ENTER 1 or 2 2

ENTER OPTION FOR SPREAD AND IMPACT RATE VALUES:
1 DEFAULT VALUES
2 SUPPLIED BY USER
ENTER 1 or 2 2

ENTER DATA INPUT MODE:
1 FROM ONLINE INPUTS
2 FROM BATCH INPUTS
ENTER 1 or 2 1

ENTER STAND DATA SOURCE:
1 FROM SURVEY RESULTS
2 FROM USER INPUTS
ENTER 1 or 2 1

ENTER REFERENCE NO. (8 CHARACTERS) RREST.TS
ENTER CURRENT STAND AGE, PROJECTED AGE AND GROWTH CYCLE (YRS) (3I3)
40,50,5

DEFAULT VALUES ARE AS FOLLOWS:
        RANDOM SERIES FOR CENTER LOCATIONS      555,666
        NO. CENTERS (IN SAMPLE):                25 (MAXIMUM)
CONFIRM? (Y OR N) Y

DEFAULT VALUE FOR STANDARD SPREAD RATE IS 175.0 CM/GROWTH CYCLE
        CONFIRM? (Y OR N) N

ENTER SPREAD RATE (CM/GROWTH CYCLE) (20F4.0)
125,125,130,130,150,150,170,170,180,180
```

DEFAULT VALUES FOR PERCENT INCREMENT LOSS PER YEAR SINCE INFECTION:

YEAR 1-5	5%
YEAR 6-10	10%
YEAR 11-15	20%
YEAR 16-20	50%
YEAR 21-25	80%
YEAR 26+	100%

CONFIRM? (Y OR N) Y[a]

DEFAULT VALUES FOR IMPACT SEVERITY FACTORS BY STAND AGE AT WHICH INFECTION IS INITIATED:

YEAR 1-5	20.00	YEAR 6-10	10.00
YEAR 11-15	5.00	YEAR 16-20	2.50
YEAR 21-25	2.00	YEAR 26-30	1.75
YEAR 31-35	1.50	YEAR 36-40	1.25
YEAR 41-45	1.00	YEAR 46-50	0.90
YEAR 51-55	0.90	YEAR 56-60	0.80
YEAR 61-65	0.70	YEAR 66-70	0.70
YEAR 71-75	0.60	YEAR 76-80	0.60
YEAR 81+	0.50		

CONFIRM? (Y OR N) Y[a]

ENTER STAND AGES FOR MAP OUTPUTS (2013)
(0 For No Maps) 40,50

ENTER STAND AGES FOR SUMMARY TABLE OUTPUT (2013)
(0 For No Tables) 40,50

GRAPHS REQUIRED? (Y/N) Y[a]

ENTER STAND AGES FOR SUMMARY TABLE OUTPUT (2013)
(0 For No Tables) 0 40,50

GRAPHS REQUIRED? (Y/N) Y[a]

ENTER STAND AGES FOR SAMPLING (2013)
(0 FOR NO SAMPLES) 0

INPUTS NOW COMPLETE. AWAIT TERMINATION MESSAGE,
RESULTS ARE IN FILE RREST.OUT

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[a] In this run, all default values have to be accepted individually. Keying N results in a displayed request for user values to be keyed in. These replace default values.

APPENDIX 3

Order, format, and contents of records (punch cards) required for batch operation of simulation model RREST. (Default values in brackets.)

Record No.	Column No.	Format	Variable	Value
1	1-5	F5.0	Current stand age	1-999
	6-10	I5	Projected stand age	1-999
	11-15	I5	Growth cycle (yrs)	1-100 (5)
	16-20	F5.1	Stand area (ha)	0.1-999.9
	21-28	A8	Reference no.	eight-character name beginning with a letter
2	1-3	I3	Random seed	1-999 (555)
	4-6	I3	Random seed	1-999 (666)
	7-9	I3	Number of centers	1-25 (25)
	10-12	I3	Center positions	0 = specified (1) 1 = randomized
	13-15	I3	Center angles	0 = specified (1) 1 = randomized
	16-18	I3	Center-axis incrementation factors	0 = specified (1) 1 = randomized 2 = uniform
	19-21	I3	Graph option	0 = no 1 = yes (1)
3	1-3	I3	Center X coordinates (if specified in record 2)	1-100
	4-6			
	.			
	.			
	.			
	73-75			
4	1-3	I3	Center Y coordinates (if specified in record 2)	1-100
	.			
	.			
	.			
	73-75			
5	1-3	F3.0	Center orientation angle degrees (if specified in record 2)	0-90
	.			
	.			
	.			
	73-75			

Record No.	Column No.	Format	Variable	Value
6	1-5 . . . 76-80	F5.0	Center spread rate (cm per growth cycle)	0.999 (175)
7	1-5 . . . 76-80	F5.2	Center X axis incrementation factor (if specified in record 2)	0.00-9.99
8	1-5 . . . 76-80	F5.2	Center X axis incrementation factor (if specified in record 2)	0.00-9.99
9	1-4 . . . 77-80	F4.0	Growth loss (percent per growth cycle)	0-100 (see Table 1)
10	1-5 . . . 76-80 .	F5.2	Severity factor	0.01-99.99 (see Table 2)
11	1-5 . . . 76-80	F5.0	Center sizes (square metres)	1-99999
12	1-3 4-6 . . . (n x 3) + 3	I3 I3	Number of sampling times (n) Stand ages for sampling (yrs)	0-20 0—projected stand age
	(n x 3) + 6	I3	No. of grids per sample	2-10
	(n x 3) + 9	I3	No. of transects per grid	2-25
	(n x 3) + 12	I3	Axis to be used as baseline	1 = X axis 2 = Y axis
	(n x 3) + 15	I3	Sampling method	1 = random with replacement 2 = random, no replacement 3 = random grids, systematic 4 = specified transect positions
	(n x 3) + 18	I3	Random seed for transect position	1-999
	(n x 3) + 21	I3	Random seed for transect position	1-999

Record No.	Column No.	Format	Variable	Value
13	1-3	I3	Transect positions (if specified)	1-100
	.			
	.			
	.			
	73-75			
14	1-3	I3	Number of maps to be drawn (n)	0-20
	4-6	I3	Stand ages for maps (yrs)	1-999
	.			
	.			
	.			
	(n x 3) + 3			
15	1-3	I3	Number of summary tables (n)	0-20
	4-6	I3	Stand ages for summary tables (yrs)	0-999
	.			
	.			
	.			
	(n x 3) + 3			

APPENDIX 4

ROOT ROT SPREAD AND IMPACT SIMULATOR "RREST"
BATCH OPTION INPUTS

*1

STAND AGE		GROWTH CYCLE (YRS)	STAND AREA	REFERENCE NO.
CURRENT	PROJECTED			
40	80	5	50.0	RRESTTST

$2

RANDOM NO. SEEDS		INFECTION CENTERS				GRAPH OPTION
		NO.	COORDS	ANGLES	SPREAD	
111	333	25	0	1	1	1

← OPTION CODES FOR COORDS, ANGLES, SPREAD 0 = SPECIFIED, 1 = RANDOM
SPREAD 2 = UNIFORM

$3 CENTER X COORDINATES (OMIT IF COORDS OPTION ≠ 0) SEE FOOTNOTE NO. 1

10	10	10	20	20	20	30	30	30	40	40	40	50	50	50	60	60	60	70	70	70	80	80	80	90	90

$4 CENTER Y COORDINATES (OMIT IF COORDS OPTION ≠ 0) SEE FOOTNOTE NO. 1

10	20	30	10	20	30	10	20	30	40	50	60	40	50	60	40	50	60	70	80	90	70	80	90	70	80

$5 CENTER AXIS ANGLES (OMIT IF ANGLES OPTION ≠ 0) SEE FOOTNOTE NO. 1

Ø6 BASIC SPREAD RATES (CM/GROWTH CYCLE) SEE FOOTNOTE NO. 2

175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175	175

$7 X AXIS SPREAD RATE FACTOR (OMIT IF SPREAD OPTION ≠ 0) FOOTNOTE NO. 1

$8 Y AXIS SPREAD RATE FACTOR (OMIT IF SPREAD OPTION ≠ 0) FOOTNOTE NO. 1

Ø9 GROWTH REDUCTION %/GROWTH CYCLE – SEE FOOTNOTE NO. 2

5	10	20	50	80	100	100	100	100	100	100	100	100	100	100	100	100	100								

Ø10 IMPACT SEVERITY FACTOR/GROWTH CYCLE – SEE FOOTNOTE NO. 2

20.00	10.00	5.00	2.50	2.00	1.75	1.50	1.25	1.00	1.00	1.00	0.90	0.90	0.80	0.80	0.70										

$11 INITIAL CENTER SIZES (SQ. M) - SEE FOOTNOTE NO. 1

100	100	100	500	500	500	750	750	750	1000	1000	1000	1500	1500	1500	1500
2000	2000	2000	2000	5000	5000	5000	7500	7500							

▲12

SURVEY				SAMPLING			
NO. TIMES	STAND AGES	NO. GRIDS	NO. TRANS	BASE LINE	METHOD	RANDOM NOS	
1	40	2	4	1	3	111	333

13 SPECIFIED TRANSECT LOCATIONS (IN % OF BASELINE LENGTH, OMIT IF METHOD ≠ 4)

▲14 MAP OPTION

NO. MAPS	STAND AGES		
2	40	80	

▲15 SUMMARY TABLE OPTIONS

NO. TABLES	STAND AGES			
4	20	40	60	80

▲ MANDATORY INPUTS

$ OMIT IF SURVEY RESULTS ARE USED

Ø OMIT IF DEFAULT SPREAD AND IMPACT RATES ARE USED

FOOTNOTE NO. 1 ENTER AS MANY AS THE NUMBER OF CENTERS SPECIFIED (MAX. 25)

NO. 2 ENTER AS MANY AS THE NUMBER OF GROWTH CYCLES UP TO PROJECTED STAND AGE (MAX. 20 CYCLES)

APPENDIX 5

Examples of outputs from root rot simulation model RREST

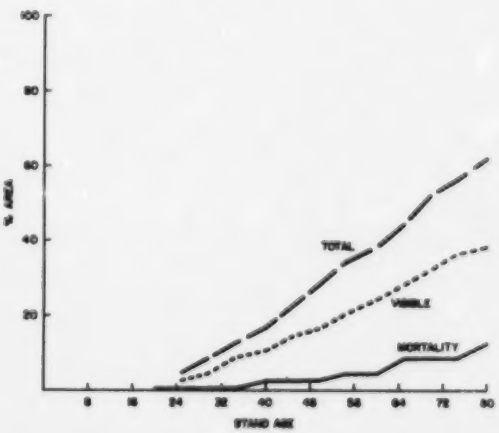
Appendix 5-1. Reference No.: RRESTTST; standard spread rate is 1.75 m in this iteration; iteration number 16; sample area 8.3 ha; stand age 80

NO.	CODE	CENTER COORDINATES RANDOM	ANGLE OF ROTATION RANDOM	X AXIS RATE UNIFORM	Y AXIS RATE UNIFORM	AREA (VISIBLE	PERCENT INFECTION)
1	A	92 , 86	23	1.00	1.00	291.7	0.35
2	B	1 , 95	58	1.00	1.00	625.0	0.75
3	C	68 , 27	8	1.00	1.00	350.0	0.42
4	D	13 , 57	31	1.00	1.00	1166.7	1.40
5	E	7 , 47	79	1.00	1.00	650.0	0.78
6	F	85 , 21	31	1.00	1.00	650.0	0.78
7	G	28 , 42	6	1.00	1.00	1050.0	1.26
8	H	28 , 4	46	1.00	1.00	983.3	1.18
9	I	68 , 60	19	1.00	1.00	1208.3	1.45
10	J	98 , 71	8	1.00	1.00	1125.0	1.35
11	K	92 , 98	80	1.00	1.00	1141.7	1.37
12	L	1 , 38	17	1.00	1.00	458.3	0.55
13	M	27 , 89	18	1.00	1.00	1875.0	2.25
14	N	86 , 20	45	1.00	1.00	1875.0	2.25
15	O	83 , 44	29	1.00	1.00	1700.0	2.04
16	P	19 , 37	73	1.00	1.00	1075.0	1.29
17	Q	72 , 97	59	1.00	1.00	1416.7	1.70
18	R	12 , 42	70	1.10	1.10	1325.0	1.59
19	S	61 , 40	58	1.10	1.10	2308.3	2.77
20	T	65 , 30	36	1.10	1.10	1533.3	1.84
21	U	94 , 52	51	1.10	1.10	2225.0	2.67
22	V	9 , 31	15	1.10	1.10	1666.7	2.00
23	W	95 , 84	11	1.10	1.10	1641.7	1.97
24	X	55 , 18	79	1.10	1.10	2391.7	2.87
25	Y	18 , 18	61	1.10	1.10	2591.7	3.11

Appendix 5-2. Root rot summary at stand age 80; area of stand sampled equals 8.3 ha

VISIBLE INFECTION	
Area (m^2)	33 325.0
Area (%)	40.0
Increment loss (%)	85.6
Mortality area (%)	32.3
TOTAL INFECTION	
Area (m^2)	53 320.0
Area (%)	64.0
Increment loss (%)	53.5
Mortality area (%)	20.2
TOTAL STAND	
Increment loss (%)	34.2
Mortality area (%)	12.9

Appendix 5-3. Graph of percent area infected over time.



POOR

QUALITY

ORIGINAL